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Water distribution system modeling and optimization: a case study

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Abstract

In the last years, the scientific literature has reported an increasing use of hydraulic models to describe water distribution systems (WDS). Hydraulic models represent tools for managing the complexity of WDSs, and a number of optimization methods have been proposed to improve the performance of these infrastructures. However, because of the lack of available data on WDSs many works have only considered synthetic WDS with idealized behaviour or small-sized WDSs with simple topology and limited complexity. This lack of complex case studies has often hindered the demonstration of the potential of hydraulic models and of the optimization approaches relying on their use. In this work, we present a case study about a real large WDS. The system is composed of approximately 3000 pipes (>170 km) and 3000 demand nodes (corresponding to 50,000 users) that are spread across a hilly area over a 200 m elevation gradient. Water is provided by ten wells and it is distributed by five pumping stations and four tanks at different elevations. Pump operation is partly automatically controlled by water levels in tanks and partly by a fixed temporal schedule. This complexity results in a nontrivial hydraulic behaviour that is well reproduced by our hydraulic model. The model is also used with a multi-objective genetic algorithm solver to identify different operational scenarios that lead to a reduction of energy consumption and water leakages.

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*Keywords:*Modeling; WDS; Optimization; MOGA; Pumping

1. Introduction

The growing urbanization, the development of new technologies, the increased awareness of users, and the needs dictated by environmental sustainability require water distribution networks (WDNs) to be increasingly efficient. These purposes stimulate the scientific community to propose novel approaches able to face new problems by employing quantitative predictive tools [e.g., 1,2,3,4].

In this picture, a typical problem occurring in advanced societies is the existence of a huge number of old WDNs that have not been upgraded and are managed following heuristic rules, which often correspond to conditions that have partially become outdated [5]. These infrastructures urge attention and their management can derive much benefit from the use of new scientific physically-based tools.

The present work falls in this class of problems and shows the improvements that can be achieved in a real medium-sized network by a suitable new pump scheduling. The considered network supplies water to a population

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of nearly 50,000 people and it is fed by ten pumping wells, and the total pipeline length is about 170 km. Therefore, the network is not only a theoretical benchmark model and is well-representative of several cases in Europe.

We focus on the optimization of the pipe scheduling in order to minimize the cost of pumping energy. This problem is widespread, is not trivial, and needs sophisticated mathematical techniques to be efficiently solved [6]. To this aim, we have applied the innovative *WDNetXL* code to pumping optimization. *WDNetXL* is a system tool created by one of authors [7] entailing the latest research advancements in WDN planning, analysis, and management. In particular, a Multi-Objective Genetic Algorithm (MOGA) approach is used for the optimization problem.The work aims it to demonstrate on a real case that significant improvements are possible, without making large investments but simply managing existing resources in a more appropriate way.

2. Methods

2.1. Description of case study

The scheme of the considered WDN is shown in Figure 1. The WDN serves a hilly area extending over approximately 30 km^2 with elevations ranging between 300 and 490 m a.m.s.l. The WDN is divided in a lower, an intermediate, and an upper district whose daily average demands are 82, 120, and 6 l/s, respectively. Most of the demand is given by residential users, with the additional contribution of an industrial zone in the eastern part of the lower district.

Fig. 1. Scheme of the WDN analyzed in the present work. The colormap represents terrain elevation.

The WDN provides water to an approximate population of 50,000 inhabitants with an average demand of 218 l/s. Minimum and maximum daily fluctuations correspond to 0.45 and 1.45 times the average demand, respectively. The network pipes have an overall length of 170 km, and their diameters range between 25 and 600 mm. Water is supplied by ten wells in three distinct source areas in the southeastern (61% of the daily demand), northeastern (8%), and western (31%) zones. The WDN also includes 10 pumps (G11-G15, G51-G53, G61-G62) for water extraction at the three well areas, 5 pumps in two booster pumping stations (M16-M18 and M31-M32) and three pumps (M19, M21, M42) which are present as emergency replacement of other pumps and are currently not in use.

Four tanks of different sizes are present in the WDN. The largest tank (H40 – 12,000 m^3) is located in the intermediate district and provides the storage capacity of the WDN. A second, smaller tank (H20 – 800 m^3) is also located in the intermediate district at a slightly lower elevation as a connection between the lower and the intermediate districts of the WDN. The lower district hosts the third tank (H10 – 1,400 m^3) near the southeastern well area, where water is temporarily stored to cope with unexpected malfunctioning of the pumps. Finally, a small tank (H41 – 80 m^3) is present in the upper district to provide water to a low number of users with high elevations.

The dynamics of the network is regulated by a set of controls to avoid excessive filling or emptying of tanks. Nine pumps (G11-G15, M16-M18, M41) are controlled by tank levels as summarized in Table 1. The remaining seven pumps are either permanently active (G51-G53, G61-G62) or are switched on/off (M31-M32) according to a fixed temporal schedule.

Table 1. Pump switch controls before and after the optimization.

Pump	Controlling tank	Original		Optimized	
		On	Off	On	Off
G11	H20	6.30	7.30	2.85	4.10
G12	H20	6.15	7.15	3.35	6.10
G13	H20	6.00	7.00	3.85	6.10
G14	H10	8.30	8.90	8.40	8.80
G15	H10	8.40	9.00	8.40	8.80
M16	H20	5.70	6.70	2.60	5.35
M17	H20	5.90	6.90	2.85	5.35
M18	H20	5.50	6.50	5.15	5.55
M41	H41	2.40	3.60	0.50	3.25

2.2. Hydraulic model

The analysis and optimization of WDN described in the previous section requires a mathematical model to predict the hydraulic behavior of the network. In this work, the *WDNetXL* code has been employed to develop the hydraulic model of the WDN. *WDNetXL* is a tool for carrying out simulation, design and optimization of water distribution systems [7]. The code is able to perform pressure-driven simualtion, background leakages [4,8] and different components of demand [9] of water flow and has a built-in MOGA solver that can be used to address different optimization problems such as pipe sizing, pump scheduling, and WDN segmentation. Pipe leakages are modeled

The function *Tank Scheduling* has been employed to identify a new set of pump controls that minimize the energy consumption for water pumping. The function employs a MOGA to optimize the tank levels at which the pumps are switched on/off. The MOGA simultaneously minimizes: (1) the total energy cost over the 24h simulation period, and (2) a cost function that penalizes solutions with node pressures below a threshold value (20 m) which would not allow to deliver the required water demands to users. An additional constraint is imposed at each tank to ensure that the level at the end of the simulation is at least equal to the starting level, thus excluding solutions that would lead to the progressive emptying of tanks.

In order to consider the technical constraints of the network, the optimization problem focused on nine of the sixteen active pumps that are installed in the WDN. Specifically, only the pumps whose functioning is controlled by levels of tanks (Table 1) have been considered in the optimization. Pumps G51-G53 and G61-G62 are always active to avoid the presence of turbidity from the wells in case of pump shutoff and reactivation, and they have hence been kept unchanged. Pumps M31-M32 are currently operated under a temporal schedule which is manually adjusted by WDN technicians to deal with unexpected changes in the user demands. These pumps have also been excluded from the optimization to maintain the possibility of manual pump regulation as desired by the water provider.

3. Results

The new switch levels identified by the optimization are compared with the original ones in Table 1. Controlling levels have been remarkably decreased for the three pumps G11-G13, with a reduction that ranges between 1 and 3 m. The new switch levels imply that pump G11 will operate only occasionally, because when the level of H20 drops below 3.85 and 3.35 m then pumps G13 and G12 are sequentially turned on. Pump G11 would be activated only if the level further decreases below 2.85 m. This pump would also be the first one to be turned off (4.1 m), while G12 and G13 would be active until the tank level reaches 6.10 m.

A similar change is found for the booster pumps M16-M18 which connect tanks H10 and H20. Compared to the original configuration in which the working load was divided among the three pumps in a relatively equal way, the new switch levels lead to a more prominent use of M18. This pump is turned off as soon as the level in H20 decreases below 5.15 m, while M17 and M16 are only switched on when the level drops below 2.85 and 2.60 m, respectively. The switch off level is instead very similar for all the three pumps (5.35-5.55 m).

The remaining pumps are less affected by the optimization. Switch levels of pumps G14 and G15 are only marginally modified (up to 20 cm). Changes in switch levels for M41 are more relevant but they do not lead to a significant change in energy consumption by this pump (see below). However, an advantage of the wider range of switch levels is given by the lower number of on/off cycles during the day and also by the enhanced water turnover in tank H41.

Figure 2 displays the changes in the tank levels determined by the optimized pump controls. The Figure shows how the level of tank H20 fluctuates around a mean value that is much lower than for the original configuration. The temporal dynamics of the level of tank H10 is instead only slightly affected by the optimization. The behavior of tank H40, whose level is not used as switch control for any pump, remains the same before and after pump optimization. This fact demonstrates the robustness on the new set of controls, which preserves the overall hydraulic functioning of the WDN. Finally, the new controls favour a better use of tank 41 with wider level fluctuations that exploit the whole tank volume and reduce the risk of water stagnation in poorly mixed parts of the tank.

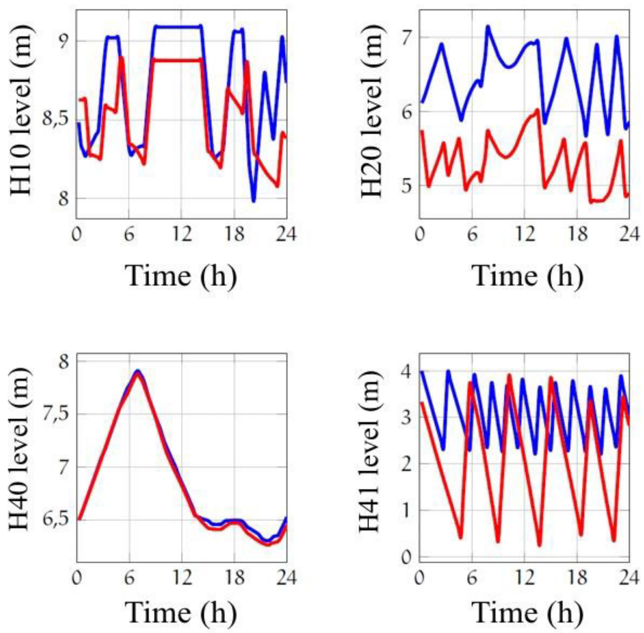

Fig. 2. Comparison between levels of the four tanks before (blue line) and after (red line) optimization.

The impact of optimization on energy consumption for water pumping is shown in Figure 3, which compares the daily energy request of each pump in both the original and the optimized configurations. As a consequence of the introduction of the optimized controls, pump G11 becomes inactive, and its stop is compensated by a more intense use of pumps G12 to G15. A careful examination of the energy consumptions reveals that this change results in a net decrease of the energy that is required by this group of pumps. A similar change occurs for pumps M16 and M17, which are switched off and replaced by M18 that originally remained always inactive because of the interplay between switch controls. Again, this modification corresponds to a lower energy consumption, although the advantage is less significant because of the lower energy required by pumps M16-M18 compared to G11-G15.

As anticipated, the optimization resulted only in a very slight reduction in the energy consumption of pump M41, although the new switch controls remarkably affected the dynamics of the controlled tank H41 (see Figure 2). As expected, consumptions of pumps that were not included in the optimization show no variations after the optimization.

Combining the effects of the changes summarized in Figure 3, the model predicts a decrease in the daily energy consumption of 740kWh/d for the whole WDN. On the basis of the current electricity price, this reduction in the energy consumption results in an expected saving of approximately 38,000 €/year.

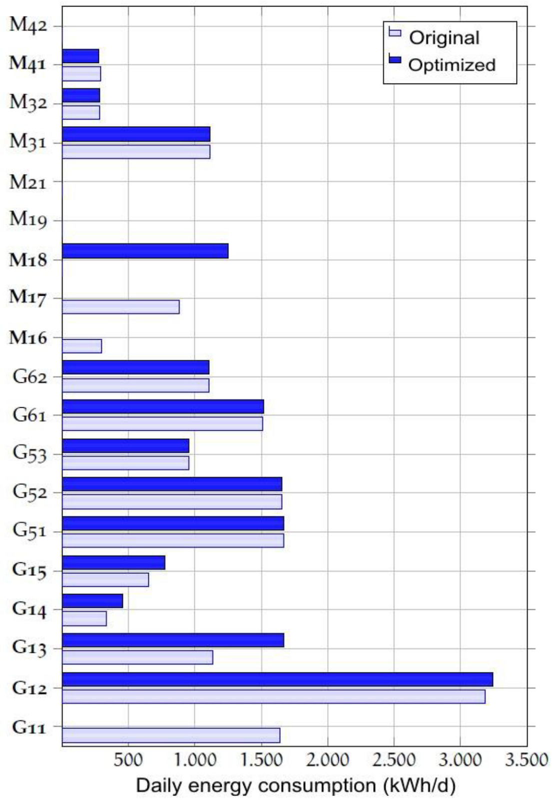

Fig. 3. Daily energy consumptions of pumps before and after optimization. Pumps marked in bold were considered in the optimization.

4. Conclusions

This work has considered as case study a real WDN of a medium-sized town with 50,000 inhabitants and water demands from both residential and industrial users. The hydraulic functioning of this network is not trivial because of (1) the high number of users, (2) the presence of districts with different elevations, (3) the resulting complex and highly looped WDN topology, and (4) the presence of 15 active pumps to extract water from wells and supply it to the high-elevation districts through booster pumping stations. Moreover, the activation of five well pumps and four booster pumps is regulated by automatic switch controls based on the levels of three different tanks.

The need for multiple pumping stations results in a considerable energy consumption, but the structural and operational complexity of the WDN results hampers the identification of effective actions to reduce the amount of required energy for pump operation. In this context, the use of *WDNetXL* has proved useful to analyze the hydraulic behavior of the WDN and to search for a better regulation of the pumps by changing the level controls at which pumps are turned on/off.

The MOGA approach implemented in *WDNetXL* successfully identified a new set of switch controls that result in a net reduction of the daily energy requirement without adverse effects on the WDN hydraulic behaviour. Beside reducing the energy consumption, the identified configuration also leads to a better use of some tanks, either enhancing water turnover within the tank or reducing average tank levels and consequently pipe pressures and leakages. The proposed modifications can be easily implemented without significant costs, and they hence represent an example of how physically-based modeling approaches of WDN hydraulic dynamics can support water providers in the management and optimization of real complex distribution networks.

References

[1] Ostfeld, A., Uber, J., Salomons, E., Berry, J., Hart, W., Phillips, C., Watson, J., Dorini, G., Jonkergouw, P., Kapelan, Z., di Pierro, F., Khu, S., Savic, D., Eliades, D., Polycarpou, M., Ghimire, S., Barkdoll, B., Gueli, R., Huang, J., McBean, E., James, W., Krause, A., Leskovec, J., Isovitsch, S., Xu, J., Guestrin, C., VanBriesen, J., Small, M., Fischbeck, P., Preis, A., Propato, M., Piller, O., Trachtman, G., Wu, Z., and Walski, T. (2008). The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms, J. Water Resour. Plann. Manage., 134(6), 556–568.

[2] Z.S. Kapelan, D.A. Savic, G.A. Walters, A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks, Journal of Hydraulic Research, 4(5) (2003), DOI:10.1080/00221680309499993.

[3] L.S. Araujo, H. Ramos, S.T. Coelho, Pressure Control for Leakage Minimisation in Water Distribution Systems Management, Water Resour. Manage., 20(1) (2006), 133-149.

[4] O. Giustolisi, D.A. Savic , Z. Kapelan, Pressure-driven demand and leakage simulation for water distribution networks. J. Hydr. Eng., 134(5) (2008) 626–635.

[5] G. Pelletier, A. Mailhot, J. Villeneuve, Modeling Water Pipe Breaks—Three Case Studies, J. Water Resour. Plann. Manage., 129(2) (2003), 115–123.

[6] J. Nicklow, P. Reed, D.A. Savic, T. Dessalegne, L. Harrell, A. Chan-Hilton, M. Karamouz, B. Minsker, A. Ostfeld, A. Singh, E. Zechman, and ASCE Task Committee on Evolutionary Computation in Environmental and Water Resources Engineering, State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management, J. Water Resour. Plann. Manage., 136(4) (2010), 412–432.

[7] O. Giustolisi, D.A. Savic, L. Berardi, D. Laucelli, An excel-based solution to bring water distribution network analysis closer to users, in Proceedings of Computer and Control in Water Industry (CCWI), Exeter, U. K., edited by D. A. Savic et al., 2011, vol. 3, pp. 805–810.

[8] G. Germanopoulos, A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models. Civil Eng. Syst., 2(3) (1985) 171–179.

[9] O. Giustolisi, T.M. Walski, A Demand Components in Water Distribution Network Analysis. J. Wat. Resour. Plan. Manage., 138(4) (2012) 356 -367.